

METHOD OF COMPRESSING IMAGES OF ARBITRARILY SHAPED OBJECTS

FIELD OF THE INVENTION

This invention relates to the field of data compression. In
5 particular, this invention is drawn to rate optimizing data compression.

BACKGROUND OF THE INVENTION

Continuous tone images refer to images that have a virtually
unlimited range of color or shades of gray. Photographs, for example, are
continuous tone images. Digital hardware, however, is limited to
10 expressing color or tone within a finite number of bits or even a single bit
(i.e., "on" or "off"). Typically the continuous tone image is decomposed
into an array of picture elements (pixels), each element capable of
representing a finite number of colors or shades. Gray scaling and
dithering are two processes used to approximate continuous tone images
15 within the limitations of digital hardware. The digital representations of
images simplify reproduction, storage, modification, and distribution of
the images.

Once the continuous tone image is discretized into digital form, the
digital form may be further processed to reduce storage requirements
20 through compression. Compression eliminates information in a manner
that results in either no visually perceptible differences or only acceptable
visually perceptible differences between the digitized source image and the
reconstructed image.

Some approaches to image compression entail direct manipulation
25 of the spectral content. Reducing the spectral energy without regard to
other factors frequently does not achieve optimal storage results due to
rate influencing elements such as quantization and entropy encoding that
are present in spectral content manipulating compression processes.

SUMMARY OF THE INVENTION

In view of limitations of known systems and methods, methods and apparatus for compressing source images are provided.

5 A method of manipulating spectral content of a block of pixels for compression includes the step of classifying each pixel within a selected block of pixels as relevant or irrelevant. A forward transform is applied to the selected block to generate a coefficient block. The coefficient values are modified to generate a modified coefficient block subject to a set of pre-determined constraints including a constraint that the relevant pixels
10 have a same value in an inverse transformation of the modified coefficient block as in the selected block.

Another method of manipulating spectral content of a block of pixels for compression includes the step of providing a source block of pixels from a source image. The pixels are classified as either modifiable or
15 nonmodifiable. A forward transform is performed on the selected block to generate a coefficient block. The coefficient block is quantized. At least one coefficient is subsequently modified to produce a corresponding zero quantized coefficient subject to a plurality of constraints. In particular, the coefficient is modified without altering pixel values of an inverse
20 transform that correspond to nonmodifiable pixels in the selected block.

Other features and advantages of the present invention will be apparent from the accompanying drawings and from the detailed description that follows below.

BRIEF DESCRIPTION OF THE DRAWINGS

25 The present invention is illustrated by way of example and not limitation in the figures of the accompanying drawings, in which like references indicate similar elements and in which:

Figure 1 illustrates decomposition of an 8x8 block from a source image of an arbitrarily shaped object into an image plane and a mask.

Figure 2 illustrates a method of changing selected pixel values to improve the compression rate.

Figure 3 illustrates one embodiment of a block oriented compression process.

5 Figure 4 illustrates a zig-zag processing order for entropy encoding coefficients.

Figure 5 illustrates one embodiment of a process for de-compressing an image compressed with the method of Figure 3.

Figure 6 illustrates the routing of blocks for compression.

10 Figure 7 illustrates a method of modifying the spectral content of a selected block of pixels subject to a plurality of constraints.

Figure 8 illustrates an alternative embodiment of a method of modifying the spectral content of a selected block of pixels subject to a plurality of constraints.

15 Figure 9 illustrates another embodiment of a method of modifying the spectral content of a selected block of pixels subject to a plurality of constraints

DETAILED DESCRIPTION

Block compression algorithms are prevalent in image processing applications. Regardless of the shape of the image, the image data is captured in blocks for processing by the block compression algorithm. Some blocks may consist entirely of pixels representing portions of the source image. Other blocks may include pixels representing portions of the source image and pixels that are not associated with the source image as a result of the shape of the block not conforming to the shape of the image. Still other blocks may consist entirely of pixels that are not associated with the source image at all.

Figure 1 illustrates a selected 8x8 block 110 of pixels from a sample discretized source image containing an arbitrarily shaped object 102.

30 Portions of the selected block corresponding to the arbitrarily shaped object

are indicated by the shaded pixels. In one embodiment, each pixel has an associated 8 bit value such that up to 256 distinct colors or gray levels may be realized (i.e., 0-255).

The selected block is decomposed into encodeable planes. A
5 graylevel selected block 110 might be decomposed into a block 120 and a mask 130. In an alternative embodiment, the source image block may be decomposed into a plurality of planes and associated masks, each associated with a distinct color plane of the image.

Block 120 is simply the source block 110. Mask 130 consists of a
10 plurality of "1"s and "0"s that indicate whether a particular pixel from block 120 forms a portion of the arbitrarily shaped object (e.g., pixel 114) or the background (e.g., pixel 112). The mask effectively identifies the pixels of block 120 that are to be preserved and enables discrimination of the arbitrarily shaped object from its background. The mask thus inherently
15 identifies selected block pixels as "relevant" or "irrelevant" with respect to the arbitrarily shaped object of interest.

The block compression algorithm is applied to block 120. Typically the mask is stored with the compressed data to aid in reconstructing the source image from the compressed data. When the source block is
20 reconstructed from the compressed data, the mask is then used to identify the relevant pixels. The amount of compression achievable is a function of the amount of acceptable loss of information of the source block, the compression algorithm selected, and the features of the image in the block. Recognizing that the particular combination and position of pixel values
25 has an affect on the amount of compression, one method of data compression effectively modifies the values of irrelevant pixels to achieve greater compression.

Block 120 is redrawn as block 140 with "X"s used to emphasize the location of pixels that are "don't cares" or "irrelevant" based on the mask
30 130. The values of pixels marked with an "X" are not important because they will be excluded with the mask 130 anyway. Although the value of

these “don’t care” pixels are irrelevant to the reconstruction of the arbitrarily shaped object, the value of the pixels may affect the compression rate of block 120. Accordingly, the encoding technique can be modified to change the values of these “don’t care” pixels in order to achieve greater compression efficiencies. This approach will not affect the reproduction quality and does not require modification of the decoding algorithm.

There are many contexts under which some pixels may be deemed modifiable due to their irrelevance to the reconstruction of the source image. Frequently, an original source image is decomposed into multiple planes for compression. For example, an image may be decomposed into separate color planes for processing. An image may be decomposed into foreground/background planes which are used in conjunction with a mask to specify which plane the pixel is to be sourced from during reconstruction of the source image. An arbitrarily shaped object in front of a background, for example, may be discriminated from the background through the use of a mask that identifies pixels that form a portion of the arbitrarily shaped object rather than the background. Such a mask is useful when the background itself is not of interest. In this case, the mask inherently identifies relevant and irrelevant pixels and thus indicates the pixels that may be modified.

Figure 2 illustrates one method of compressing data as the operation might be conducted in the spatial domain. In step 210, a source block consisting of a plurality of pixels is selected from the source image. In step 220, the plurality of pixels is categorized into at least two classes. A first class of pixels is designated as irrelevant or modifiable. The second class is designated as relevant or nonmodifiable. For example, pixels associated with the arbitrarily shaped object are designated as nonmodifiable. Pixels associated with the background or otherwise not associated with the object of interest are designated as modifiable. Referring to Figure 1, mask 130 inherently determines the class that each corresponding pixel in the source block belongs to (e.g., 1 = nonmodifiable, 0 = modifiable).

One technique for compressing the digital representation of source image data includes the step of transforming the spatial domain image data into frequency domain data. Transformation from the spatial domain into the frequency domain is also referred to as a forward transformation.

5 Forward transformation is analogous to a harmonic analysis of the source image. A forward transform is used to represent the spatial image data as linear combinations of basis functions. The coefficients for these basis functions are determined during the transformation process.

10 The basis coefficients are then quantized or thresholded to eliminate contributions from the corresponding basis function to achieve some level of compression. The remaining coefficients are then re-ordered or run-length encoded or otherwise processed to facilitate further compression of the image data. The resulting compressed image data is then available for storing, distribution, or for further processing. This is the basic technique
15 promulgated by the Joint Photographic Experts Group (JPEG).

Typically, the greater the number of zero-valued quantized coefficients, the greater the rate of compression. Accordingly, in step 230, the values of the modifiable pixels are modified to decrease the number of non-zero quantized coefficients. The modifiable pixels are modified so
20 that a quantized forward transform of the modified block has a greater number of zero values than a quantized forward transform of the selected block. This operation reduces the "rate" of the compressed image, where "rate" is a reference to the storage requirements of the compressed image. The operation thus increases the compression efficiency or rate efficiency
25 of the image encoder.

The manner in which pixels are modified depends upon the specifics of the compression algorithm. The Joint Photographic Experts Group and the Motion Picture Experts Group (MPEG) have each promoted popular image compression and encoding architectures that manipulate
30 spectral content to achieve data compression. JPEG compression is frequently used for static images such as those encountered in facsimile or

standard printing applications. The MPEG format is used for dynamic images or movies. The basic process has been promulgated by JPEG and is in widespread use today. Although JPEG utilizes a Discrete Cosine Transformation (DCT), specific implementations of the forward transform, quantization, and entropy encoding blocks is left to the implementer.

Figure 3 illustrates one embodiment of a block-based process for compressing an image in greater detail. The image encoder 320 processes a discretized source image 310 to produce compressed image data 390.

Encoder 320 processes the source image 310 as a plurality of 8x8 source blocks. A forward transformation is performed on each 8x8 source block. Each 8x8 source block is a 64-point discrete signal that is a two-dimensional spatial function of x and y . The DCT is one of many transforms that can be used to represent signals as linear combinations of basis functions. Although the DCT is the selected transform for JPEG compression, other linear forward transforms such as the Fourier transform and the Discrete Sine Transform (DST) may be used.

The forward DCT is a harmonic analyzer that converts the 64 point discrete signal into 64 orthogonal basis signals. Each orthogonal basis signal represents a two dimensional spatial frequency forming the spectrum of the 8x8 source block. The output of the forward DCT is a coefficient block identifying the amplitude of each of these orthogonal basis signals. The amplitudes are referred to as DCT coefficients and the values are determined by the discrete 64 point input signal.

A source image is sampled as a two dimensional array of discrete values, $s(x,y)$. Performing a two dimensional forward transform entails calculating the basis coefficients $c(u,v)$ such that $s(x,y)$ can be expressed as a linear combination of basis functions. In one embodiment (DCT), a forward transform involves calculating $c(u,v)$ such that:

$$s(x,y) = \sum_{u=0}^{N-1} \sum_{v=0}^{N-1} c(u,v) \lambda(u,v) \cos\left(\frac{(2x+1)u\pi}{2N}\right) \cos\left(\frac{(2y+1)v\pi}{2N}\right)$$

$$\begin{cases} u, v \in [0, N-1] \\ \lambda(0, v) = 1/N \\ \lambda(u, 0) = 1/N \\ \lambda(u, v) = 2/N \text{ for } u, v \neq 0 \end{cases}$$

In one embodiment of the DCT, the coefficients $c(u, v)$ are calculated as follows:

$$c(u, v) = \lambda(u, v) \sum_{y=0}^{N-1} \sum_{x=0}^{N-1} s(x, y) \cos\left(\frac{(2x+1)u\pi}{2N}\right) \cos\left(\frac{(2y+1)v\pi}{2N}\right); \quad u, v \in [0, N-1]$$

- 5 The two dimensional DCT transform involves identifying the coefficients for a set of basis functions that collectively make up the image.

Referring again to Figure 3, quantizer 340 quantizes the DCT coefficients in accordance with a quantization table 342. Different
 10 quantization table 342. The quantized $c(u, v)$ may be calculated as follows:

$$c^Q(u, v) = INT\left(\frac{c(u, v)}{q(u, v)}\right)$$

where "INT" is an integer function to ensure the result is an integer.

The quantization table permits different step sizes for different basis functions. The quantization table is thus a 64 element table, one element
 15 for each spatial frequency. Generally, step sizes for higher frequency basis functions are larger than the step sizes for lower frequency basis functions. The step sizes are typically chosen at the perceptual threshold for the visual contribution of the corresponding cosine basis function. The perceptual threshold are functions of the source image characteristics,
 20 display characteristics, viewing distance, etc. Thus the choice of quantization table may be application dependent.

After quantization, entropy encoding is used to efficiently represent the quantized coefficients. Entropy encoder 350 uses entropy encoding table 352 to generate the compressed image data 390.

25 Briefly, the number of previous zeros and the bits needed to represent the current quantized coefficient value form a pair. Each pair has its own code word assigned through a variable length code. Huffman,

Shannon-Fano, and arithmetic coding are examples of commonly used variable length coders. The more often a given element occurs, the smaller the number of bits that are used for the corresponding code. The JPEG encoder outputs the code word for the pair and then a code word for the current quantized coefficient (also assigned by a variable length coder).

After processing a block of quantized DCT coefficients, the JPEG encoder writes a unique end of block sequence and then moves to the next block. After finishing all blocks, the JPEG encoder writes an end-of-file marker. Tables 352 and 342 may be incorporated into the compressed image data to facilitate reconstruction.

The result of quantization is that many of the DCT coefficients have been reduced to zero. In particular, coefficients corresponding to higher frequency cosine basis functions tend to be zero. Ordering quantized DCT coefficients to obtain longer strings of zero-valued elements improves the rate efficiency of the entropy encoder, particular at the point where any remaining quantized DCT coefficients to be encoded are all zero. Accordingly, the entropy encoder encodes the quantized DCT coefficient block in a zig-zag manner progressing from quantized coefficients associated with lower frequency basis functions to the quantized coefficients associated with higher frequency basis functions as illustrated in Figure 4.

The upper left corner of block 410 corresponds to the DC term ($u, v=0$). The DC terms are differentially encoded across individual encoded blocks. The remaining AC terms represent higher frequency cosine basis functions when progressing towards the lower right corner. The JPEG entropy encoder need only encode up to the highest frequency non-zero quantized coefficient before writing an end of block. Any other coefficients are presumed to be zero.

The zig-zag scan order tends to group the number of non-zero elements at one end of the string of elements to be encoded. When the higher frequency basis coefficients are zero, the zig-zag scan order groups

the zero elements at the end of the string of quantized coefficients being coded, thus improving the rate efficiency of the entropy encoder. The JPEG encoder need not encode beyond the last non-zero quantized coefficient in the scan order. Given that the higher order frequencies are likely to be zero, the zig-zag scan order thus increases the compression efficiency of the JPEG encoder.

Figure 5 illustrates a decoder 520 for generating a reconstructed source image 590 from the compressed image data 510. An entropy decoder 530 and entropy decoder table 532 are used to recover the quantized DCT coefficients. Dequantizer 540 uses dequantizer table 542 to generate the dequantized DCT coefficients. In one embodiment, dequantizer table 542 is the same as quantizer table 342. An inverse transform is performed on the dequantized coefficients to generate the reconstructed source image. For JPEG applications, block 550 performs an inverse DCT transformation on the dequantized DCT coefficients to obtain the reconstructed source image 590.

The basic spectral manipulation encoding process can be modified to permit modification of pixel values that are irrelevant to reconstruction of the source image, but might have significant effects on rate efficiency.

The 64 pixels in a block are denoted as vector \underline{z} which is comprised of two smaller vectors \underline{y} and \underline{x} such that

$$\underline{z}^T = \{\underline{y}^T, \underline{x}^T\}$$

where \underline{y} is the set of N_y relevant pixels and \underline{x} is the set of $64-N_y$ irrelevant pixels. The 64x64 2D DCT transformation matrix for the vector is denoted T so that the coefficient set \underline{c} is given by $\underline{c} = T\underline{z}$.

One approach might be to solve for the vector \underline{x} in \underline{z} that minimizes the energy of the AC coefficients while leaving the known vector \underline{y} unaffected. The cost function to be minimized is then given by

$$\begin{aligned} J(\underline{x}) &= \sum_{i=1}^{63} c_i^2 \\ &= \|\underline{c}\|^2 - c_0^2 \end{aligned}$$

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$$\begin{aligned}
&= \|\underline{z}\|^2 - c_0^2 \\
&= \|\underline{x}\|^2 + \|\underline{y}\|^2 - c_0^2 \\
&= \sum_{i=0}^{63-N_y} x_i^2 + \|\underline{y}\|^2 - c_0^2
\end{aligned}$$

The DC coefficient for 2D DCT is given by:

$$\begin{aligned}
c_0 &= \frac{1}{8} \sum_{i=0}^{63} z_i \\
&= \frac{1}{8} \sum_{i=0}^{N_y-1} y_i + \frac{1}{8} \sum_{i=0}^{63-N_y} x_i
\end{aligned}$$

When $J(\underline{x})$ is partially derived with respect to each element x_i of \underline{x} and equated to zero, each element is found to yield the same optimal value given by:

$$x_i = \frac{1}{N_y} \sum_{i=0}^{N_y-1} y_i$$

Thus the optimal interpolation for the modifiable pixels in terms of minimizing energy of AC coefficients is the solution that sets the values of all the modifiable pixels to the average of the nonmodifiable pixels. This approach might be a good starting point but it ignores the effects of differential DC coding and the particulars of the block compression algorithm entropy encoder.

The goal is to find \underline{z} that minimizes the rate by maximizing zero runs along the reverse zig-zag scanning path while satisfying other constraints. For example, any modifiable z_i must be assigned a pixel value within the realizable range and z_i for nonmodifiable pixels should not change giving:

$$\begin{aligned}
z_i &= y_i \quad i = \{0, 1, \dots, N_y - 1\} \\
0 &\leq z_i \leq 255 \quad i = \{N_y, \dots, 63\}
\end{aligned}$$

Consider the DCT coefficients for the modified block. Some coefficients are quantized to zero while others are quantized to non-zero

values. The locations (i.e., indices) of the coefficients that can be quantized to zero form the set I_{zero} such that

$$I_{\text{zero}} = \left\{ i \mid -\frac{q_i}{2} < c_i < \frac{q_i}{2}; i \in \{0, 1, \dots, 63\} \right\}$$

The coefficients are scanned in reverse zig-zag scan order to find the first one, c_j , that is not quantized to zero. If it is possible to “push” the coefficient to zero without violating the other constraints then there is a solution \underline{z} which satisfies the previous constraints:

$$\begin{aligned} z_i &= y_i \quad i = \{0, 1, \dots, N_y - 1\} \\ 0 &\leq z_i \leq 255 \quad i = \{N_y, \dots, 63\} \end{aligned}$$

as well as the following constraint obtained from the I_{zero} set:

$$-\frac{q_i}{2} < c_i = \underline{t}_i^T \underline{z} < \frac{q_i}{2}, i \in I_{\text{zero}},$$

(i.e., no zero-quantized coefficient may become non-zero quantized) that also satisfies the following constraint:

$$-\frac{q_j}{2} < c_j = \underline{t}_j^T \underline{z} < \frac{q_j}{2}$$

The term \underline{t}_i represents the i^{th} row of DCT matrix T. Each zero quantization constraint is a linear inequality constraint. The existence of a feasible solution is a Phase 1 linear programming problem which can be readily solved using techniques such as the simplex method. Modification of coefficient values will not affect the value of relevant pixels as a result of the equality constraints limiting such modifications. Relevant pixels in the selected block will have the same value as corresponding pixels in an inverse transform of the modified coefficient block. The inverse transform of the modified coefficient block is a modified selected block.

If a solution exists, then the index of the new zero quantized coefficient is added to the I_{zero} set and \underline{z} is updated to the feasible solution. If, c_j is not zero quantizable, then the method proceeds to the next non-zero coefficient proceeding in the reverse zig zag order. The process may be repeated until all non-zero quantized coefficients have been tested.

Although the resulting solution satisfies all the constraints, the solution may not be optimal in the sense of minimizing the energy of the coefficients. In addition to maximizing the length or number of zero runs, the energy of the non-zero quantized coefficients should be minimized to reach the lowest rate. The minimum energy solution at each stage minimizes:

$$E(\underline{z}) = \left(c_0 - \frac{8}{Ny} \sum_{i=0}^{Ny-1} y_i \right)^2 + \sum_{i=1}^{63} c_i^2$$

subject to the previously established constraints:

$$-\frac{q_i}{2} < c_i = \underline{t}_i^T \underline{z} < \frac{q_i}{2}, i \in I_{zero}$$

$$z_i = y_i \quad i = \{0, 1, \dots, Ny-1\}$$

$$0 \leq z_i \leq 255 \quad i = \{Ny, \dots, 63\}$$

The dc value is considered differentially with respect to the mean of the relevant pixel values. The above problem is a quadratic cost function subject to a series of linear equality and inequality constraints. A quadratic program may be applied to identify a solution. The quadratic solver needs only to be invoked after the successive Phase 1 linear programs.

The successive linear programs yield solutions with increasing numbers of zero quantized coefficients which may result in the energy of the remaining DCT coefficients becoming higher than that of the optimal average interpolated block. If the energy increases too much, the rate may increase even if zero runs have been maximized.

To avoid this outcome, the quadratic program may be invoked at each stage after a feasible solution has been found. In this case, the quadratic program uses a stopping criterion based on the ratio of the coefficient energies of the newest modified block versus that of the average interpolated block. If the energy E of the modified selected block exceeds a pre-determined proportion T_E ($T_E > 1$) of the energy E_0 of the average interpolated block then the optimization is terminated to avoid leading to a higher rate.

Figure 6-7 illustrate the process in graphical form. In step 610, a block of pixels containing at least a portion of a source image is selected. The selected block pixels are classified as relevant or irrelevant in step 620.

If the block contains a mix of relevant and irrelevant pixels as determined by step 630, then the optimization process of Figure 7 is invoked in step 650 before the standard block compression algorithm (e.g., JPEG) is applied in step 670. If the block consists only of irrelevant pixels as determined by step 650, then the block is modified by assigning all the pixels a common pre-determined value such as 0 or the average of the relevant pixels from a preceding block in step 660 before being processed in step 670. If the block consists only of relevant pixels (i.e., nonmodifiable), then the standard block compression algorithm is applied in step 670 without modifying the selected block.

Figure 7 illustrates the pre-compression optimization process for blocks having a mix of relevant and irrelevant pixels. The irrelevant pixels are initialized in step 710. In one embodiment, the irrelevant pixels are set to a value corresponding to the average pixel value of the relevant pixels in the selected block. In step 712, the energy of the selected block (after initialization) is computed as E_0 .

In step 720, a coefficient block is generated by applying a forward transform on the selected block. In step 730, the location of all zero quantized coefficients is stored in array I_{zero} .

Proceeding in the reverse zig-zag order, the location of a selected non-zero quantized coefficient is identified in step 740. In step 750, the value of the selected coefficient is calculated for the current \underline{z} .

Step 752 determines whether the selected coefficient is zero quantized. If so, then the location of the coefficient is appended to the I_{zero} set of other zero quantized coefficients in step 770.

If the selected coefficient is not zero quantized, then step 754 determines whether a feasible solution exists that results in a zero quantized coefficient subject to the previously identified constraints. In

one embodiment, a Phase 1 linear program is used to identify such a feasible solution. In one embodiment, the simplex method is used to identify feasible solutions. If no feasible solution exists, processing continues to step 780.

5 If a feasible solution exists, a quadratic program is used to identify
the minimal energy solution for \underline{z} in step 760. This new \underline{z} has an
associated energy, E , which is calculated in step 762.

Step 764 determines whether $\frac{E}{E_0} > T_E$, where T_E is an acceptable

threshold value for the proportion of E to E_0 . If $\frac{E}{E_0} \leq T_E$ then the coefficient

location is added to the I_{zero} set of other zero quantized coefficients in step 770 and processing continues with step 780.

Proceeding from either step 754 or step 770, a check is performed in step 780 to determine whether there are any more coefficients to be processed. If not, then the modification process for the coefficient block is completed in step 790. Otherwise, the process continues with the next non-zero quantized coefficient by returning to step 740.

The optimization process repeats steps 740-780 until all non-zero quantized coefficients have been processed or until the energy of the result exceeds the pre-determined threshold.

Although the process above describes the basic method when the block is initialized by assigning the average value of the relevant pixels to all of the irrelevant pixels, the computations may be less complex when operating in a translated domain. By using the translational transformation:

$$z'_i = z_i - \frac{1}{N_y} \sum_{i=0}^{N_y-1} y_i$$

the quadratic cost function can be converted to a simple energy function. All of the other constraints must similarly be appropriately shifted by the average relevant pixel value. The irrelevant pixels, for example, are initialized to zero.

In one embodiment, the process stops the first time a feasible solution cannot be found regardless of whether additional coefficients remain to be processed. This approach maximizes the length of the last run on zeroes. The last run has the most significant effect on coded rate for JPEG encoders due to the principle of operation of the entropy encoder.

Figure 8 illustrates an alternative embodiment of the method of Figure 7 that stops searching for additional non-zero quantized coefficients after encountering a coefficient for which there is no feasible zero quantized solution. Comparing Figures 7-8, once step 854 determines that no feasible solution exists, the process terminates in step 890 instead of preparing to handle any subsequent non-zero quantized coefficients in step 880.

Figure 9 illustrates another variation in which the quadratic program is performed only at the end stage (i.e., after all coefficients have been processed). Thus if step 954 determines a feasible solution exists, the coefficient location is still added to I_{zero} in step 970. The quadratic program is applied in step 960, however, only after there are no more coefficients to process as determined by step 980. The process is then completed in step 990.

The method of spectral content manipulation tends 1) to increase the number of zero quantized coefficients, and 2) to prioritize increasing the number of consecutive zero quantized coefficients associated with higher frequency basis functions. Given the idiosyncrasies of entropy encoders, this enables the JPEG encoder to represent the relevant image using less data before issuing an end of block.

One particular advantage of the improved process is that no modification needs to be made to the decoder. Thus although greater computational resources may be required to generate the compressed image data, no additional resources are required for decoding the compressed data. In addition, there is no difference in the relevant portion of the image reconstructed from compression without pixel

manipulation and the image reconstructed from compression with pixel manipulation because the relevant pixels are preserved.

In the preceding detailed description, the invention is described with reference to specific exemplary embodiments thereof. Various
5 modifications and changes may be made thereto without departing from the broader spirit and scope of the invention as set forth in the claims. The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense.

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